THE DEVELOPMENT OF A PREDICTION MODEL FOR THE ACOUSTIC QUALITY OF FANS

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SUMMARY

A model for the prediction of the acoustic quality of fans is currently under development in a project funded by the German research association for air and drying technologies. This paper describes key aspects of the model development and its application. The model provides a link between psychoacoustic indicators reflecting perceived differences in sound character and fan noise specific level adjustments (level penalties) on a dB-scale, which are determined in extensive listening tests with a special measurement method.

INTRODUCTION

Fan sounds are a typical part of environmental noise that humans hear in different everyday situations. Especially loud and unpleasant fan sounds can be disturbing or even annoying in certain application cases and contexts. Unpleasant sounds can also play a major role in the evaluation of a product and they might be detrimental for the appreciation of a certain product, e.g. in the context of HVAC sounds in cars [1, 2].

Although it is well known that many technical acoustic measures like A-weighted sound pressure levels have limitations in adequately depicting the perception and evaluation of sound, they are still widely used because they are easily communicated and commonly used by engineers. However, using only a level-based measure as a sole indicator can be misleading in an optimization process especially for sounds differing in spectral content or temporal signatures [3, 4, 5]. In order to enable a successful development of more pleasant fan sounds, it is therefore necessary to understand and characterize the perceptually relevant aspects of fan sounds and their impact on the evaluation of the sound [5, 6].

A model for the prediction of the acoustic quality of fans is currently under development in a project funded by the German research association for air and drying technologies (FLT e.V.). Based on extensive listening tests and a factor analysis, the most important perceived sound characteristics could be identified for a broad variety of different fan sounds. Utilizing the output of a standardized loudness model, two indicators were developed that characterize the most important spectral aspects and distinguish three major groups of fan sounds [6]. The acoustic quality of the fan test sounds was assessed with an indirect listening test method adjusting the level of a fan sound to make it equally preferred as a reference sound [7]. The level difference between test and reference sound can then be interpreted as a level penalty or level adjustment for the fan sound.

The developed prediction model links the perceived sound characteristics described by the indicators with the fan sound evaluations from the listening tests measured as level differences. Using the model, differences in sound character can be translated to a dB-value, which might be more commonly understood and more easily interpreted than values on rating scales alone.

CATEGORIES OF FAN SOUNDS

In a first study with extensive listening tests, 45 volunteer listeners have rated 35 different fan sounds with a semantic differential [6]. The semantic differential consisted of 29 adjective pairs that were rated on a 7-point scale, each. All fan sounds were equalized in A-weighted sound pressure level to 55 dB(A) and presented over headphones.

To reduce the dimensionality of the dataset and explore the latent factors, one factor analysis was applied to the adjective scales to determine the underlying perceptual space. A second factor analysis was applied to the sounds to identify groups of sounds, which have a similar rating profile. The results of both factor analyses combined (Fig. 1) show the considerable differences in the description and the assessment of the sounds although they were equalized in A-weighted level.

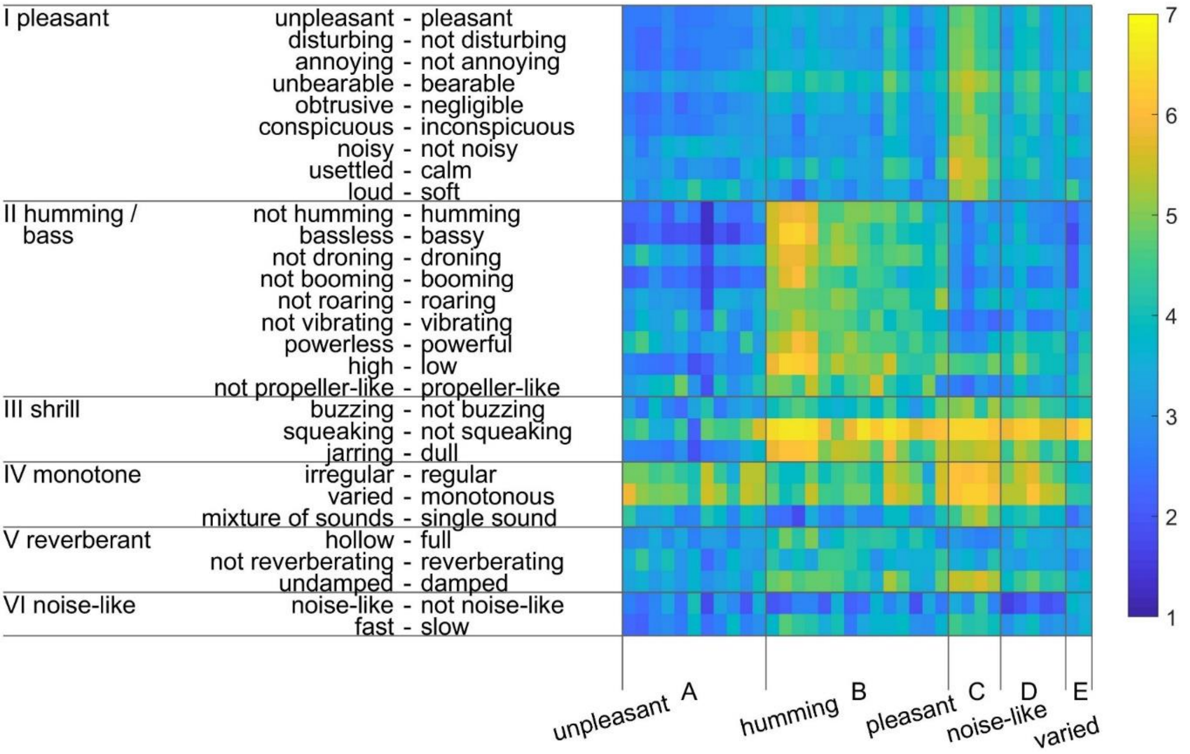

Figure 1: Average ratings of different fan sounds ordered according to the perceptual dimensions (I to VI) and the groups of sounds (A to E) determined with a semantic differential and factor analyses. Each column represents one fan sound and colors indicate the rating on the 7-point scale for each of the 29 adjectives in the 29 rows.

Each column in Fig.1 reflects the average judgments of one sound indicated by the color on the adjective scales from 1 to 7 in the 29 rows. Yellow color indicates e.g. pleasant, not disturbing and not annoying sounds and blueish color indicates unpleasant, disturbing and annoying sounds on the first factor. The adjective rows are ordered according to their loadings onto the six factors (I - VI) extracted with the first factor analysis. Similarly, the sound columns are ordered according to their loading onto the five factors (A - E) extracted with the second factor analysis. Pleasant sounds (from group C) and unpleasant sounds (from group A) can be mainly distinguished on the dimension shrill (III) which seems to be related to the spectral content of the sounds. The second largest group (B) consisted of humming sounds that were rated in between the pleasant and unpleasant sounds on the first dimensions (I).

INDICATORS TO CHARACTERIZE FAN SOUNDS

In order to describe the pleasant, unpleasant and humming sounds, two indicators were developed [4]. Both indicators are based on the specific loudness output of the loudness model according to the German DIN standard [8][1]. The indicator N_{ratio} describes the loudness ratio between mid-frequency content (in the range from about 200 Hz to 500 Hz) and high frequency content (above about 1 kHz) with a transition between the two frequency ranges. The indicator N_{low} describes the relative loudness contribution of low frequency content below about 200 Hz to the overall loudness. Details on the indicators can be found in [4].

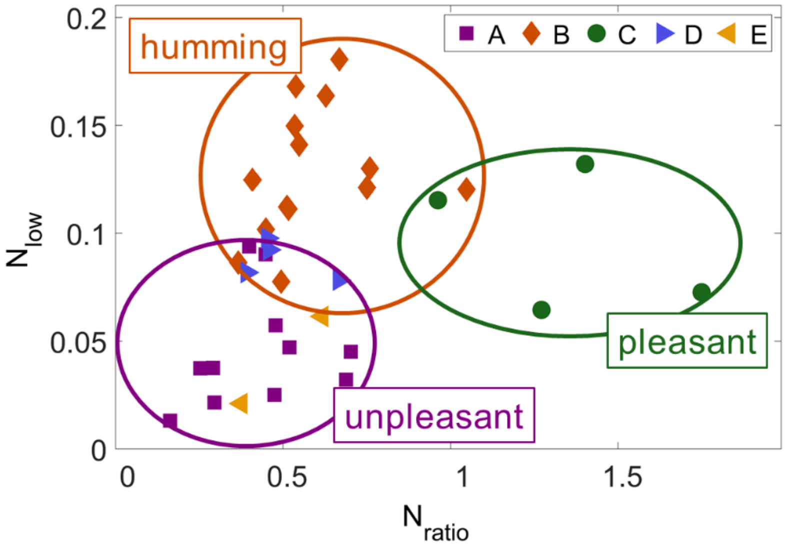

Figure 2: Positions of the sounds from the semantic differential experiment as a function of the developed indicators N_{ratio} *and* N_{low} *allowing for a distinction between the three identified main groups of the unpleasant (A), humming (B) and pleasant (C) fan sounds.*

Figure 2 shows the positions of all 35 fan sounds with respect to the two indicators. The three most important groups of fan sounds, (A) unpleasant, (B) humming and (C) pleasant, are well distinguished by the two indicators. The unpleasant sounds (A) all have low values for N_{ratio} and N_{low}. The humming sounds (B) also have low to medium values for N_{ratio} but high values of N_{low}. In contrast, the pleasant sounds (C) have medium values of N_{low} and high values for N_{ratio}.

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[1] The calculation of the indicators could also in principal be realized with the loudness model defined in the ISO 532-1 standard.

DETERMINATION OF PREFERENCE EQUIVALENT LEVELS AND THEIR INTERPRETATION AS LEVEL ADJUSTMENTS

The results of the semantic differential listening tests clearly showed that the A-weighted sound pressure level does not reflect the differences in evaluation between the tested sounds simply because it is not capable to describe the variety of sound characteristics encompassed in the sounds. Nevertheless, it can be very beneficial to establish a link between sound characteristics, the perceived psychoacoustic sensations and a level measure on a decibel scale because of the widespread usage of level-based measures to characterize noise immission (sound pressure levels) as well as emissions (sound power levels).

One way, to overcome the shortcomings of level-based measures to more accurately reflect subjective noise assessments is the introduction of level adjustments or level penalties [9]. The summation of the measured sound pressure level and the level adjustment results in a rating level, which can be better suited to express the disturbance or annoyance effects of a certain noise situation. Several standards provide guidelines for the determination of rating levels for noise immissions in the neighborhood [10] or noise immisions at the work place [11]. However, the mentioned standards define level adjustments only for impulsive noise and prominent tonal components. Furthermore, the decision about the magnitude of the level adjustments is usually in the hand of the engineer[2].

In the frame of the present project, the acoustic quality of the fan test sounds was determined in listening tests with an adaptive procedure varying the level of a test sound until it becomes equally preferred as a reference sound that is fixed in level (L_{ref}) [7]. The level of the test sound at the point of subjective equality (PSE) L_{pref} is the preference equivalent level and the difference $\Delta L_{pref} = L_{pref} - L_{ref}$ can be interpreted as a level penalty or level adjustment.

The measurement procedure and exemplary results are shown in Fig. 3. Sounds that were part of the unpleasant (violet squares) or humming group (orange diamonds) in the study with the semantic differential required a level reduction of up to 15 dB compared to the reference sound to become equally preferred. Sounds from the pleasant group (filled green circles) only need about 5 dB to reach equal preference with the reference sound. The determined preference equivalent levels include all sound characteristics that are used by the listeners to make their decision in the listening tests. In this way, the method is not limited to selected sensations, like impulsiveness or tonality, which are listed in the mentioned standards to set a level adjustment [10, 11], but it includes all actually perceived aspects of the sounds.

In the lower part of Fig. 3, the median results from the listening tests are plotted over the indicator N_{ratio}. A linear regression was fitted to spectrally manipulated fan sounds (open symbols in Fig. 3) resulting in an adjusted $r^2 = 0.86$ for the training data. The evaluation of the model with all other signals (filled symbols in Fig. 3) led to a coefficient of determination of $r^2 = 0.81$, which was higher than that achieved by alternative models either based on N_{ratio} and N_{low} ($r^2 = 0.75$) or the psychoacoustic sharpness (according to DIN standard, $r^2 = 0.63$).

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[2] The German DIN 45681 standard describes a calculation method for the tone adjustment, which can be taken account of by the engineer but which is not mandatory [11].

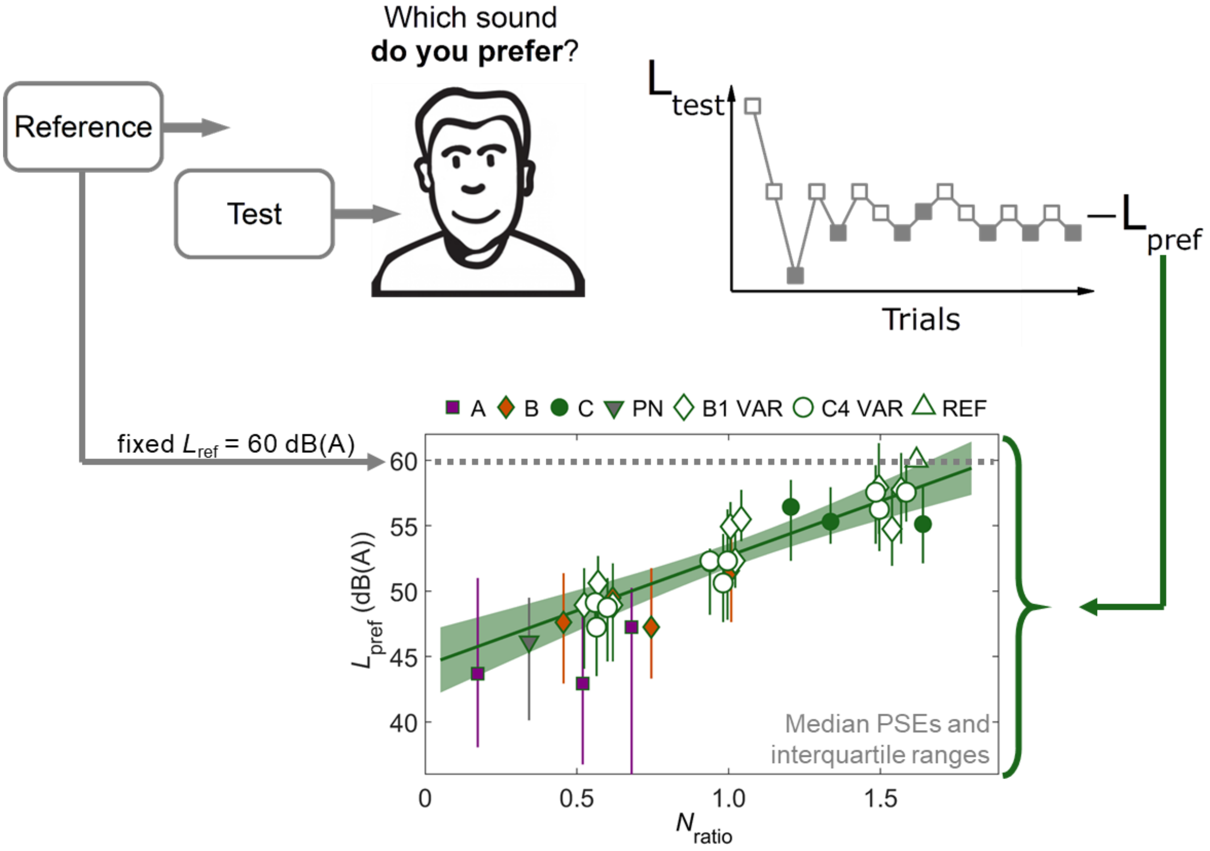


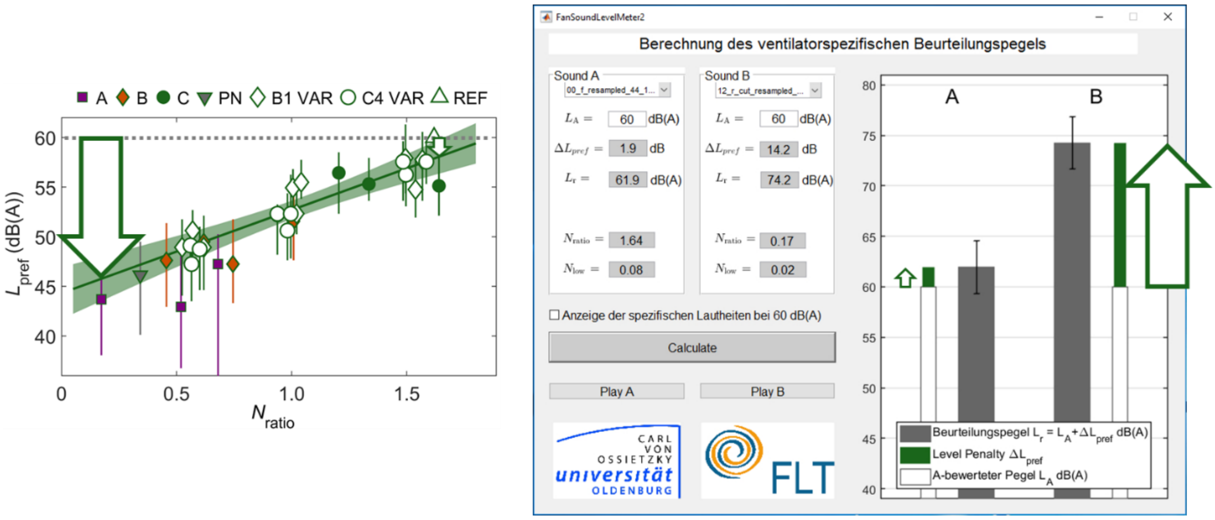
Figure 3: Test and reference sound are presented to the listener. The level of the test sound L_{test} is varied with an adaptive procedure until the test sound is equally preferred as the reference sound (open triangle) with a fixed level (here 60 dB(A). The median preference equivalent levels L_{pref} can be rather well predicted by the developed indicator N_{ratio} alone.

An analysis of questionnaire data that was collected after the listing test supported the robustness of the measurement method using an indirect measurement with a comparison against a reference sound [13]. In the questionnaires, the participants were asked retrospectively about their prior experience with fan sound in daily life. Five categories of everyday situations could be identified, in which the participants had most commonly heard fan sounds. Considerable inter-individual differences were found for the frequency how often fan sounds had been heard and the perceived annoyance evoked by fan sounds in daily life. However, a strong link between the individual prior experience and the results of the listening tests was not found in that analysis.

INTEGRATION AND APPLICATION OF THE MODEL

The developed regression model has been implemented into a software tool, shown in Fig. 4, which requires an audio file of a fan sound recording and the measured A-weighted sound pressure level. The tool calculates the two indicators N_{ratio} and N_{low} based on a calculation of the specific loudness according to the DIN standard in the background.

The level difference $\Delta L_{pref} = L_{pref} - L_{ref}$ between the preference equivalent level L_{pref} and the reference level L_{ref} is predicted by the regression model that is based on the indicator N_{ratio} alone. It is exemplarily indicated for two sounds by the two green arrows in the left plot of Fig. 4. The predicted level difference ΔL_{pref} is subtracted from the A-weighted sound pressure level of the sound to result in a level adjustment shown by the green arrows in the graphical user interface on the right side of



Berechnung des ventilatorspezifischen Beurteilungspegels

Sound A: 00_f_resampled_44_1...
$L_A =$ 60 dB(A)
$\Delta L_{pref} =$ 1.9 dB
$L_r =$ 61.9 dB(A)
$N_{ratio} =$ 1.64
$N_{low} =$ 0.08

Sound B: 12_r_cut_resampled_...
$L_A =$ 60 dB(A)
$\Delta L_{pref} =$ 14.2 dB
$L_r =$ 74.2 dB(A)
$N_{ratio} =$ 0.17
$N_{low} =$ 0.02

☐ Anzeige der spezifischen Lautheiten bei 60 dB(A)

Beurteilungspegel $L_r = L_A + \Delta L_{pref}$ dB(A)
Level Penalty ΔL_{pref}
A-bewerteter Pegel L_A dB(A)

Figure 4: Left: The level difference between the preference equivalent levels L_{pref} and the reference level (here L_{Ref} = 60 dB(A)) can be interpreted as a level penalty (green arrows indicate example predictions). Right: A software tool allows the calculation of the indicators N_{ratio} and N_{low} and the prediction of the resulting level penalty (again shown as green arrows).

Fig. 4. Thus, a level reduction ($\Delta L_{pref} < 0$ dB) due to the attenuation of a test sound compared to the reference in the listening tests, becomes an additional penalty. The software tool does a simultaneous calculation for two input signals to enable a direct comparison of two fan sounds based on the rating levels.

In the example on the right side of Fig. 4, both signals have the same A-weighted sound pressure level of 60 dB(A) but they differ in the predicted level adjustment (penalty) indicated by the arrows. For signal A, a level reduction of about 2 dB is predicted (small green arrow), for signal B the level reduction is predicted to be about 14 dB (large green arrow). This means that Signal B would require a 12 dB level reduction to make it equally preferred as signal A. The other way round, signal A could be nearly 10 dB higher in level than signal B and still have a lower rating level and thus be on average more preferred than signal B.

MODEL EXTENSION AND OUTLOOK

To extend the prediction capabilities of the existing model towards higher and lower absolute sound pressure levels, additional listening test were carried out recently [14]. The adaptive measurement of preference equivalent levels described above was repeated for a lower reference level of 45 dB(A) and a higher reference level of 75 dB(A) with the same reference signal and two groups of 24 participants, each.

Figure 5 shows the results from listening tests together with a subsample of the data that was collected for the reference level of 60 dB(A). Shown are the median preference equivalent levels as a function of the indicators N_{ratio} and N_{low} calculated at the preference equivalent level (Point of Subjective Equality, PSE) for each sound. The three-layered mesh grids, which are fitted to the data of all signals for each of the three reference levels, can be interpreted as iso-preference surfaces (similar to the isophone curves, which reflect equal loudness). The iso-preference surfaces for a reference sound level of 60 dB(A) and 75 dB(A) show a similar major influence of N_{ratio}, a minor influence of N_{low} and more or less just a shift in level between the two surfaces. For the low reference level of 45 dB(A) (the lowest surface in Fig. 5), the slope with respect to the parameter N_{ratio} is less steep than for the higher reference levels.

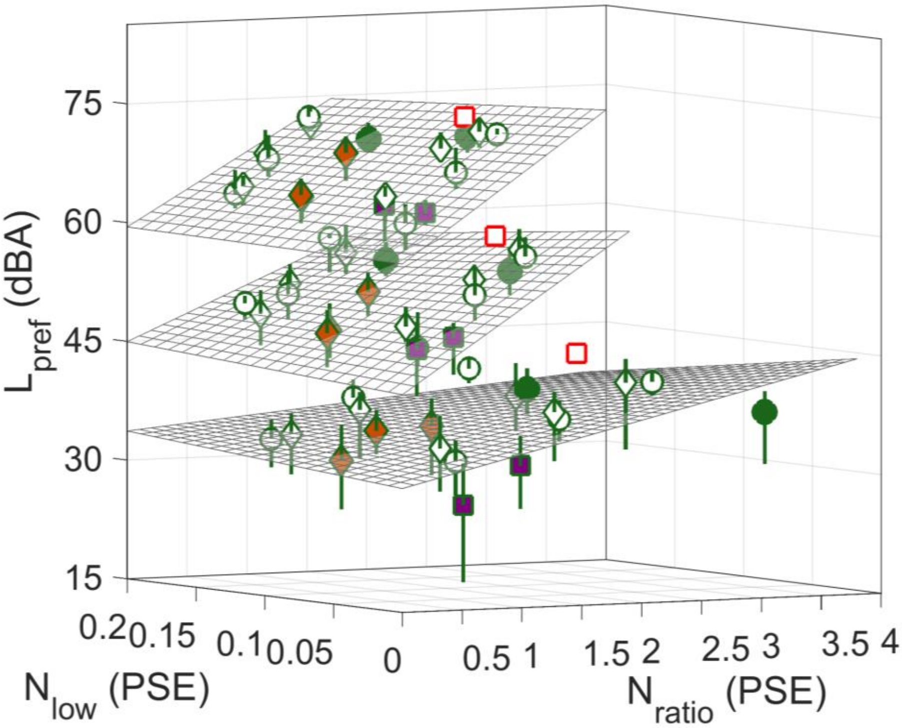


Figure 5: Preference equivalent levels of 28 different fan noise signals for 3 different reference sound levels of 45, 60 and 75 dB(A) plotted over the 2 indicators N_{low} and N_{ratio} calculated at the preference equivalent level for each sound. Fitted mesh grids reflect iso-preference surfaces. Symbols are the same as in Fig. 3.

For some of the sounds, deviations from the fitted surface are visible for the 45 dB(A) reference level. These deviations indicate the shortcomings of the two indicators at low levels and the need for additional parameters to allow for better predictions at low absolute sound pressure levels. Especially sounds containing tonal components are not well reflected by the lowest iso-preference plane based on N_{low} and N_{ratio}. Current work is focusing on the extension of the existing model including the data for 45 dB(A) and 75 dB(A) as well as the characterization of tonal fan sounds and a quantitative assessment again in the form of preference equivalent levels to enhance the prediction model.

ACKNOWLEDGEMENTS

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